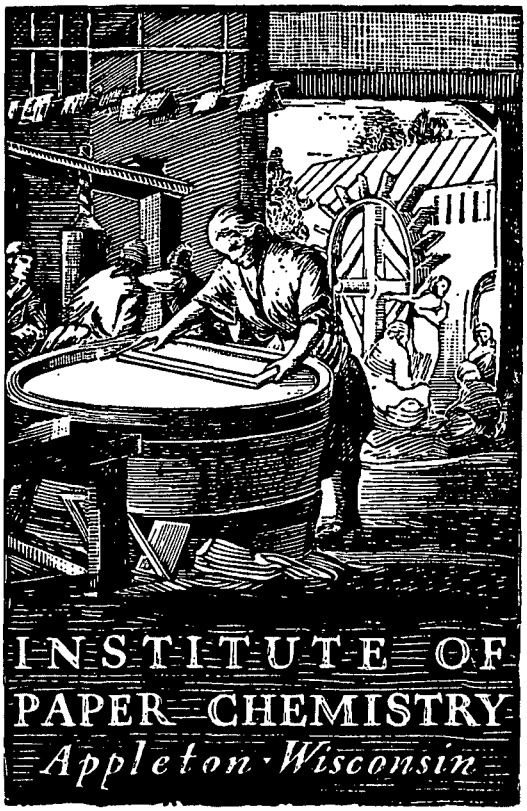


GENERAL

STUDY OF BONDING POTENTIALS OF CORRUGATING MEDIUM

Project 2696-17

Report One

A Progress Report

to

FOURDRINIER KRAFT BOARD INSTITUTE, INC.

January 15, 1976

GENERAL

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

STUDY OF BONDING POTENTIALS OF CORRUGATING MEDIUM

Project 2696-17

Report One

A Progress Report

to

FOURDRINIER KRAFT BOARD INSTITUTE, INC.

January 15, 1976

TABLE OF CONTENTS

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

STUDY OF BONDING POTENTIALS OF CORRUGATING MEDIUM

SUMMARY

The underlying hypotheses on which this study was undertaken were at least threefold: First, the water drop or its equivalent appears to be a very superficial way of characterizing the bonding potentials of corrugating medium because it is carried out on medium which has not been subjected to the calendering pressures encountered at the flute tip (reduces caliper about 33%) which would be expected to induce significant changes in sheet structure and hence, bonding characteristics. Secondly, the water absorbency methods all involve inordinately large time exposures compared to time involved on a single-facer. Third, the two paperboard properties which are considered to be of paramount importance in the type of bonding required in the corrugating operation are initial permeability of the medium by the wet adhesive and surface roughness. In keeping with the above, the study was directed to determining the correlation of these latter two parameters and bonding as measured in terms of pin adhesion. It was proposed to measure initial permeability (surface receptivity) and surface roughness by means of the nip film spreading technique employed by Wink and Van den Akker but at speeds more commensurate with conventional corrugator speed than the extremely slow speeds (fractional foot per minute) used by Wink and Van den Akker. For this purpose the IGT tester was modified to permit the spreading of a given volume of "adhesive" by means of a two roll nip similar to a single-facer adhesive transfer-paper nip at speeds of 150-450 fpm. It was recognized that the proposed approach might not be amenable to the same theoretical treatment as the slow speed plate and roll technique used by Wink and Van den Akker. However, the two roll nip and the nip film spreading rates of 150-450 fpm more nearly simulate

the adhesive transfer conditions on a corrugator. A jet cooked "solution" of Staley's oxidized starch (Stayco M) and water was used as the adhesive fluid.

During the course of the study, various other non-Newtonian and Newtonian liquids were used in the film spreading trials, however, only the Stayco M was used in the main body of the study. In addition to the evaluation of the sample mediums in terms of nip film spread results from which, hopefully, surface permeability (surface receptivity) and surface roughness could be determined, the sample mediums were evaluated for water drop, water absorbency, transverse bond and caliper. The characteristics of the paper were determined on the felt and wire side of each calendered and uncalendered sample used in this study. In addition, each medium was corrugated at progressively higher speeds on the Institute's corrugator for the purpose of determining the levels of adhesion in terms of pin adhesion as well as adhesive consumption.

The nip film spreading results obtained with the modified IGT tester and conditions used in this study at 150 and 450 fpm indicated that the film density or spread pattern changed little, if any, with increasing speed in contrast to the slow speed results obtained by Wink and Van den Akker. In the latter case the slower the spreading speed, the smaller the spread area or higher the surface density of the spread film. As a result of the insensitivity of the film spreading to rate of spreading, calculation of the two major parameters — surface receptivity and surface roughness could not be obtained from the results. However, the results obtained on the sample mediums have been statistically analyzed with regard to the relationship between the properties of the mediums and the pin adhesion strength of the single-faced board. For the latter, the adhesion value used in the correlation for each medium is the average pin adhesion strength of the single-faced board made at 200-600 fpm.

When the results of the calendered samples are considered, it may be seen that there are very small differences in the level of correlation between felt and wire side and thus the composite felt and wire should give a more realistic assessment. For the composite calendered results it was observed that the highest correlation coefficient was obtained for the relationship between the percent liner tear observed in the pin adhesion test and pin adhesion; however, the percent liner tear is not a primary function of medium quality. The transverse bond strength, measured by means of the ZDT tester exhibited the next highest correlation. Both the percent liner tear and the ZDT bond strength were significant at the 0.01 level. The film spread area correlated very poorly with pin adhesion. Because of the limited number of sample lots evaluated, the correlations should be viewed with caution because the coefficients can be greatly influenced by a few data points.

In general, it may be expected that adhesion should depend, in part, on the transverse bond strength of the medium and this probably explains the significant correlation between pin adhesion and ZDT strength. However, the correlation was greatly influenced by the results for two samples which exhibited somewhat lower ZDT strength, after calendering, and adhesion strength than the other samples. The positive sign of the correlation is also in the expected direction — the higher the ZDT strength, the higher the pin adhesion.

Neither water drop nor cold water penetration were significantly related to pin adhesion for either the felt, wire or composite calendered results although water drop exhibited somewhat higher correlation coefficients than cold water penetration. The correlations for water drop were influenced to a considerable extent by the results of two samples which also exhibited somewhat lower ZDT after calendering. Both samples exhibited quite low water drop values and low pin

adhesion strength. If these samples were omitted, the water drop values would probably be negatively correlated with pin adhesion strength which would be more in accord with the usual experience that pin adhesion tends to decrease for mediums with very high water drop numbers.

The results obtained on the uncalendered mediums show about the same trends as were observed for the calendered samples except that the ZDT strength was not significantly related to the pin adhesion strength in this case.

Based on the composite (felt and wire side) correlation, the following intercorrelations were significant at the 0.5 level:

		Correlation Coefficient
1.	Calendered samples	
	a. Pin adhesion and ZDT	0.65
	b. Log cold water penetration and log of water drop number	0.95
	c. IGT nip spread area at 150 and corresponding area at 450 fpm	0.87
	d. ZDT and log of water drop	0.54
2.	Uncalendered samples	
	a. Log water drop and caliper	0.67
	b. Log cold water penetration and caliper	0.66
	c. Log cold water penetration and log water drop	0.94
	d. IGT nip film spread area at 150 fpm and corresponding area at 450 fpm	0.84
	e. ZDT and log water drop number -	-0.60
	f. ZDT and log cold water penetration	-0.62

In general, the properties of the corrugating medium which may be expected to influence the pin adhesion strength of corrugated board are those

which: (1) affect the nature of the contact developed with the adhesive and the component, and (2) the fiber-fiber bond strength of the components.

The data obtained in this study do not warrant a comprehensive treatment in terms of analysis because it was not possible to achieve the primary objective: to determine the surface roughness and surface receptivity. It is obvious that the technique of Wink and Van den Akker is not applicable for the conditions used. Although budgetary limitations did not permit a more extensive treatment of a two roll nip film spreading at relatively high speeds the results do show the need for a comprehensive analysis of the fundamentals involved in the adhesive transfer at the single-facer. It appears obvious that speed plays a very important role in governing adhesive film thickness and transfer.

When this study was initiated it appeared that surface receptivity and surface roughness should play an important role in adhesive transfer and hence bonding. However, the results obtained with a two roll nip at high speeds indicated that probably the hydrodynamic effect was such that only surface roughness was involved — the spreading time being too small for absorption to play a significant role. Whether this is the case needs to be determined and it is suggested that this can best be done by a study directed to determining the fundamentals involved in adhesive application as related to (a) doctor-applicator-paper speed relationship, adhesive formulation, speed, paper properties, etc. It is proposed that the next step be directed to determining the fundamental parameters involved and their interrelation to the characteristics of the adhesive, speed, adhesive pick-up and paper properties.

INTRODUCTION

The current practice of evaluating the adhesion or bonding potentials of corrugating medium by means of the water drop test or equivalent would, at best, appear to be a very superficial way of evaluating this important characteristic of corrugating medium. Adequate bonding of the corrugated medium to each liner or facing is a must if one is to realize the full potential structural strength of the corrugated board. As a preliminary consideration of a better approach to the measurement of the bonding potentials of corrugating mediums, reflection should be given to the environment to which the medium is subjected and how it reacts to this environment. For example, it is well known that during the medium's passage through the corrugating labyrinth the medium at the tip of the flutes undergoes approximately a 33% permanent set as a result of the molding forces being concentrated at this point. The introduction of permanent set of such a magnitude would be expected to induce changes in sheet structure — e.g., web compaction, pore size, roughness, porosity, surface permeability, etc., — which would in turn be expected to significantly affect the bonding characteristics of the sheet. Inasmuch as the conventional test methods involve testing the medium in an unaltered state (without calendering at the flute tips), it would seem logical to question if it should be expected that the evaluation of bonding potentials on unstressed medium would correlate with the bonding behavior in the stressed (permanent set) condition encountered in actual practice.

Further, the current methods of evaluating the bonding potentials embrace a water exposure period inordinately longer than is encountered in the corrugating process. This would be expected to further complicate the relationship between actual bonding and bonding potentials determined by means of the water drop time.

The corrugating process is like so many other paper and paperboard converting operations which involve very short time interactions between the paper or substrate and the adhesive. The volume rate of strike-in of the wet adhesive and the amount of adhesive carried on the surface of the flute tip are considered to be of importance in establishing the bond between the facings and the corrugating medium. Two paperboard properties which should be of paramount importance in the type of bonding required in the corrugating operation are initial permeability of the medium by the wet adhesive and surface roughness.

Some years ago Wink and Van den Akker (1) developed an apparatus for measuring these properties of paper using a procedure in which a known volume of liquid is dispersed into a nip formed by a flat glass plate and a moving paper specimen supported by a 2-inch diameter rubber roll. As the paper moves through the nip the liquid is caused to spread over the surface of the paper — some penetrates into the paper and the balance is transported through the nip by the roughness of the paper surface. The areas and the difference in area of spread patterns obtained with the same liquid for two different velocities of the paper are theoretically related to the volume rate of penetration of the liquid into the paper and the mean depth of the irregularities of the paper surface. In their earlier work, Wink and Van den Akker determined the permeability and roughness parameters by means of graphical analysis. In essence based on theory, they developed an integral equation containing two unknowns. The assumption is made that the amount of liquid carried through the nip due to the irregularities in surface topography — roughness — will be the same per unit area at the two speeds. In addition, the amount of liquid removed from the nip by absorption is proportional to the square root of the time. Thus, one can deduce what the surface receptivity and the roughness (mean depth of the irregularities of the paper surface) would be. The graphical method has now been replaced by a computer analysis (2).

RESEARCH PROGRAM

As mentioned above, it was hypothesized that the bonding potentials of corrugating medium should be related to the surface receptivity, pe, and the roughness, h, of the corrugating medium. Project 2696-17 was undertaken to determine if the general approach — i.e., nip film spreading technique — could be used to determine the surface receptivity and roughness parameters of corrugating medium at speed levels more commensurate with conventional corrugator speeds than the very slow film spreading speeds employed by Wink and Van den Akker. Further, it was proposed that the IGT tester be modified so as to perform the nip film spreading by means of two rolls of finite radii in contrast to the plate and roll nip used by Wink and Van den Akker as the latter technique did not lend itself to the speed range of conventional corrugators. It was recognized that the proposed approach might not be as amenable to the same theoretical treatment as the slow speed plate and roll technique, however, the two roll nip film spreading technique at rates of 150-450 fpm more nearly simulates the conditions encountered at the transfer nip on the corrugator than the slow speed plate and roll nip film spreading technique. There were other departures from the plate-roll nip technique such as the use of a jet-cooked "solution" of Staley's oxidized starch (Stayco M) and water. It also should be mentioned that the spreading liquid was applied as a drop (of known volume) on the top of one of the rolls rather than being directly inserted in the nip.

IGT TESTER MODIFICATION

As mentioned, the IGT tester was modified so as to perform nip film spreading tests using two rolls in much the same way as the transfer roll on the corrugator adhesive sytem applies adhesives to the tips of the flutes. The

modifications involved the following: The existing sector of the tester was replaced by a 6.75 inch diameter aluminum wheel with a 1.5 inch width rim. The test specimens were mounted on the surface of this roll. A brass transfer roll 2.5 inches in diameter and 1.5 inches wide replaced the "ink" roll of the tester. A variable speed motor was used to drive the aluminum roll through a clutch arrangement which permitted the aluminum roll to make one revolution and stop. The brass "applicator" roll was friction driven by the corrugating medium on the aluminum roll. As may be seen in Fig. 1, the brass applicator roll, carrying the measured volume of fluid, is so positioned that it has to turn through approximately 90° to bring the fluid into the nip. Photographic measurements showed that by the time the fluid reached the nip the application roll had the same surface speed as the drive roll. The pressure system of the IGT tester was also modified by replacing the internal spring and loading screw with a cable arranged so the "applicator" roll could be dead weight loaded. For most testing, a 15.25 pound weight was applied to the cable attached to the 3:1 load multiplier of the tester to give a line load on the specimen of 30.5 pli in the absence of adhesive. The line load during the film spreading was not constant but varied inversely as the width of the film in the nip, however, the film spread width was always less than the specimen width, thus the line pressure was proportionately higher than the 30.5 pli referred to above.

ADHESIVE

Three different fluids were used in this study although the major portion of the nip film spreading was carried out with only one fluid. These are listed below:

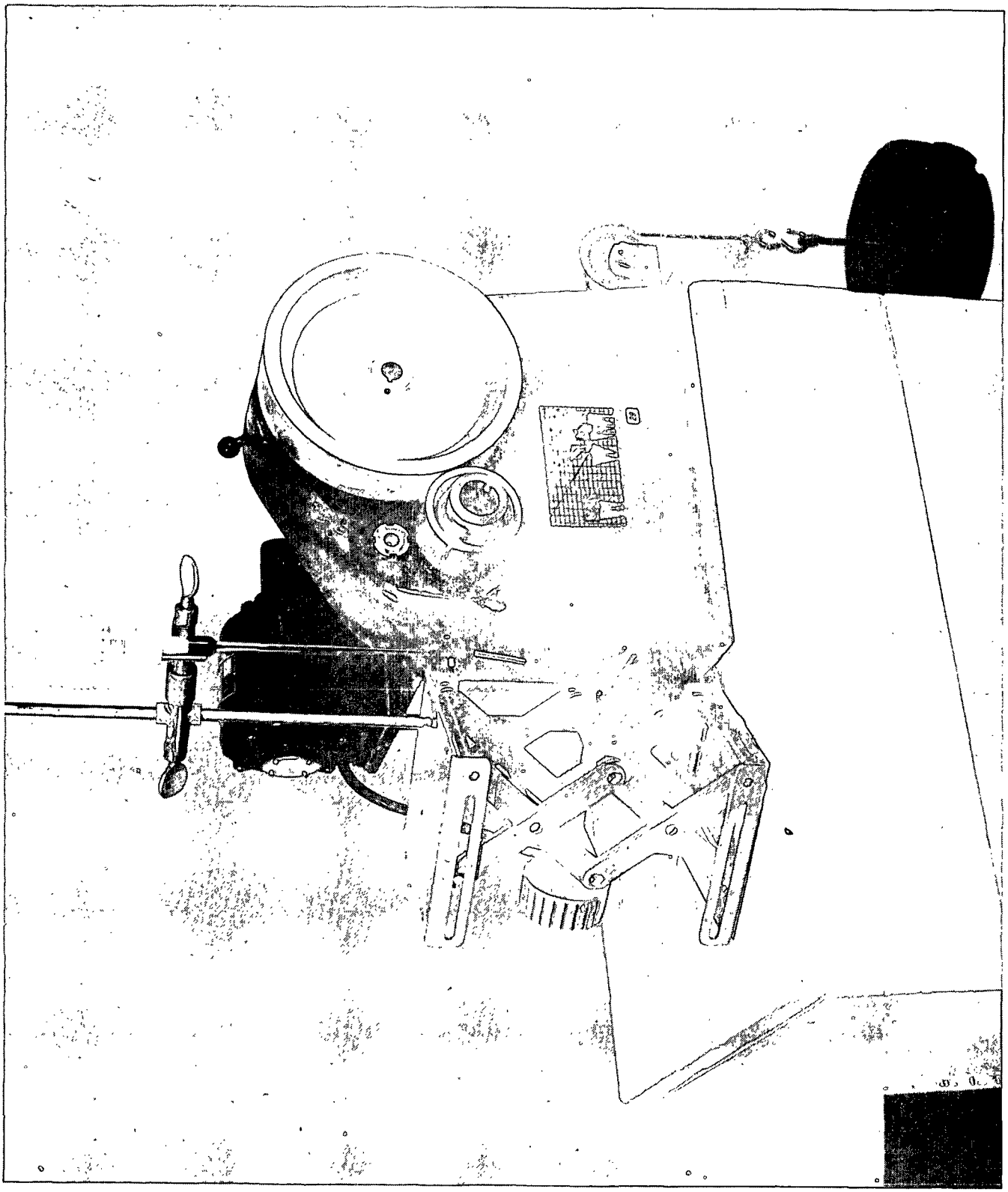


Figure 1. Appearance of Modified IGT Tester

1. Dispersion of cooked oxidized starch (Stayco M) at 25 and 12.5% solids. This was the fluid used in the major portion of the nip film spreading trials.
2. Polyvinyl alcohol solution at 4 and 8% solids.
3. Polyisobutene, 500 centipoise grade.

The Stayco starch dispersion was prepared by forming a slurry of one pound of Stayco M in three pounds of water. The slurry was cooked at 200°F in a jet cooker with a dwell time of 6 seconds. After cooking, the starch dispersion was cooled to 80°F and one gram of methylene blue dye was added. The viscosity (Stein-Hall cup) at 70°F was 27 seconds. The solids were 25%. In some of the trials the starch dispersion was at 12.5% solids.

The polyvinyl alcohol was prepared by heating an 8% solids mixture of polyvinyl alcohol and water to 195°F for 30 minutes. After cooling, the solution was diluted and used at 4% solids for some of the trials.

The polyisobutene was used as received. All trials were carried out at standard conditions.

MATERIALS

It was initially proposed that the study embrace a series of corrugating mediums at the following water drop levels:

1. Two samples in 0-20-second water drop range.
2. Two samples in 25-30-second water drop range.
3. Two samples in 50-100-second water drop range.
4. Two samples in 100-200-second water drop range.
5. Two samples in 200-400-second water drop range.
6. Two samples in 400-600-second water drop range.

However, in the interest of economy, the Technical Division of FKI reduced the number of samples to eight by omitting Items 2 and 4 above.

Each of the corrugating medium samples as received consisted of one roll of medium 12 inches wide and approximately 50 inches in diameter. In addition, one sample of 42-linerboard consisting of four rolls 12 inches wide and 50 inches in diameter was also received. The linerboard requested was to have a high fiber-fiber bond strength.

In addition to evaluation of the above mediums in terms of such properties as surface roughness, receptivity (permeability), water drop, etc., each medium was corrugated at progressively higher speeds, on the Institute's corrugator, for the purpose of determining the levels of adhesion in terms of pin adhesion as well as the adhesive consumption. The adhesive consumption was determined by adding a fluorescent dye — Uranine B — to the adhesive, extracting the dye from a known area of combined board and determining the amount of dye by measuring the degree of fluorescence which together with the adhesive-dye ratio permitted calculation of the adhesive consumption.

EVALUATION

1. Physical Characteristics of Corrugating Medium

   As mentioned previously, the transverse compression forces encountered in the molding of the flute as it passes through the corrugating labyrinth are concentrated at the flute tip and normally induce a 30-35% permanent set (loss in caliper) in the medium at the flute tip. In order to simulate this condition, a portion of each medium sample was calendered.

The portion of each medium sample selected for calendering was conditioned at 50% RH and 73°F for at least 48 hours. Forty strips (6 inches CD x 24 inches MD) were prepared for each sample. Each group of 40 specimen strips was placed in a polyethylene bag and transported to the calender area. The calender used consisted of two steel rolls, 10 inches in width and 11 inches in diameter and was operated at 45 fpm. The deadweight loading was equivalent to a line nip load of 400 pli on the 6 inches wide specimens. The two rolls were heated to 250°F during the calendering operation. The calendered samples, together with samples which had not been calendered, were evaluated for nip film spread at 150 and 450 fpm, transverse bond, caliper, water drop and cold water penetration after conditioning at standard conditions. The procedures used are described below:

a. Nip film spread

The nip film spreading test was intended to provide the basic data necessary to calculate the two parameters: (1) surface roughness, and (2) permeability or surface receptivity. The procedure used was as follows: A 1.5 by 22 inch long specimen of medium was taped at both ends to the rim of the aluminum drive roll of the modified IGT tester. The dead weight loaded brass applicator roll was brought into contact with the medium on the aluminum roll. A given volume of fluid (oxidized starch dispersion, polyvinyl alcohol, or polyisobutene) was deposited on the top center of the brass applicator roll at a position 90°

from the pressure nip. The clutch was then released which caused the motor to rotate the aluminum roll at the preset rate. The aluminum roll in turn provided the driving force for turning the brass applicator roll with the drop of "adhesive" on it so as to bring the drop into the nip where it was spread on the medium. The aluminum roll turned through approximately 300 degrees and then braked to a stop (the brass applicator roll revolved approximately two turns due to its smaller diameter). The pressure on the nip was then released and the medium strip removed from the aluminum roll and the area was measured with a planimeter initially, however, it was found that the spread area of the drop could be calculated with good accuracy by measuring the length and width of each spread pattern and using the formula:

Area = $\pi \frac{L \times W}{4}$, where L is the maximum length of spread and W is the maximum width of the spread pattern. The average of five determinations was reported to the nearest 0.01 sq inch. Both felt and wire sides were evaluated.

b. Transverse bonding strength

The fiber bond strength was measured on the conventional ZDT tester. Ten determinations were made on each sample of calendered and uncalendered medium. The readings were taken to the nearest pound and averaged to the nearest 0.1 pound.

c. Caliper

Ten caliper measurements were made on each of the calendered and uncalendered samples using a Cady micrometer. The ten readings were averaged to the nearest 0.1 point.

d. Water drop

Using Tappi Method T 432, ten water drop determinations were made on each sample, felt and wire side, calendered and uncalendered. The time in seconds for 0.1 ml of water to be absorbed was recorded to the nearest second.

e. Cold water penetration

A cold water penetration test was performed on all samples using a method suggested by Owens-Illinois, Inc. Five determinations were made on each sample, felt and wire side, calendered and uncalendered. The time in seconds for the top surface of the specimen to be at least 95% saturated was recorded to the nearest second. The general procedure was as follows:

(1) Cut test specimen 4 x 4 inches.

(2) Form "boats" by centering the 4 x 4 inch specimen over a hole in plywood block and push a rubber stopper into the hole. Twist the stopper 1/2 turn while forming the "boat." The plywood block was 7 inches square and 3/4 inch thick. The hole was cut at the angle of a No. 13 rubber stopper but with a 0.010 inch larger diameter.

(3) Place enough distilled water in an open dish so the surface area of the water is greater than the area of the bottom of the "boat."

(4) Place the test specimen on the surface of the water with the desired side up. At the same time start a stop watch or timer.

(5) Stop timer when 95% penetration of the specimen surface has been reached.

(6) Record the time in seconds for water penetration.

2. Corrugating Trials

As previously mentioned, each sample of corrugating medium was corrugated into A-flute single-faced board. For this purpose each sample of corrugating medium was corrugated at progressively increasing speeds on the Institute's corrugator with 42-lb linerboard into A-flute single-faced board for the purpose of obtaining pin adhesion and adhesive consumption results with which to correlate the properties of the medium. In an effort to reduce the effect of machine variables, all the corrugating medium samples were combined into two rolls in accordance with the following procedure: Eleven 30-ft long strips of each medium were cut and allowed to condition at standard conditions for several days. After the conditioning period, a butt roll of medium containing approximately 3,000 lineal feet of medium was placed on the rewinder and one 30-ft strip of each of the sample mediums was spliced end-to-end and wound on the butt roll with the wire side on the inside. A length of "waste" medium was then spliced in and wound on the roll and then another series of 30-ft strips were spliced and wound on the same roll. A similar length of waste medium was spliced in and wound on to the roll for a leader. This procedure was repeated until five

groups of medium samples had been wound on the composite roll each separated by a length of waste material. Under this condition of winding the wire side was bonded at the single-facer when corrugated.

A second roll was prepared as above except six series of each sample, each with the felt side on the inside of the roll, were wound on the roll.

Using the standard corrugating conditions, each roll so prepared was corrugated on the Institute's corrugator at progressively increasing speeds from 200 to 600 fpm. The leader in each case was sufficiently long on each roll to attain stable conditions at each selected speed. After the first set of samples had gone through the corrugating rolls the speed was increased to 200 fpm. Thus, as each additional set of samples was corrugated, the speed was increased in 100 fpm increments until 600 fpm was reached for the test samples "glued" on the wire side and 700 fpm for the test samples "glued" on the felt side. As the single-faced samples came off the single-facer bridge, they were laid flat on the floor to avoid creasing or damaging the samples. The single-faced board samples were evaluated as follows:

a. Pin adhesion

For each sample, five pin adhesion specimens (2 inches wide x 9 flutes long) were cut from between the finger lines from the single-faced board made at each speed level. The testing was carried out on a H&D

tester. The five readings were read to the nearest one pound and averaged to the nearest 0.1 lb/6 sq inch of specimen area.

b. Adhesive consumption

A sample of single-faced board (2 feet long) was taken at the start and end of each 30-foot strip at each speed level. Each pair of samples (start and end) were combined to give one adhesive consumption sample. The dye method described earlier was used to determine the starch pick-up. During the analysis it was found that the adhesive consumption of Sample 5541 could not be determined by this method as the water solubles in the medium itself masked the effect of the dye. All tests were made in duplicate and were averaged to the nearest 0.001 lb/M ft^2.

DISCUSSION OF RESULTS

PRELIMINARY TRIALS

After the mechanical design changes had been made to the IGT tester and the tester found to perform in accordance with the design, it was necessary to carry out a preliminary study to determine the best method of applying the fluid (simulated adhesive) and the type of spread pattern obtained.

As mentioned previously, the nip film spreading as visualized in this study, involves applying a known volume of a selected fluid to the surface of the brass applicator roll. The fluid is then caused to spread in the nip — in this case, a nip formed by two rolls of different radii. Inasmuch as the spread pattern is a function of the amount of fluid applied, it was necessary to carry out a comparison of the accuracy and reproducibility of various methods of dispersing a drop size volume of the selected liquid. A summary of the results obtained are given in Table I. The procedure selected for use in the balance of Project 2696-17 corresponds to Number 9 in Table I. In brief, this involved lowering the micrometer pipette to within a very small distance (approximately two-thirds the height of the final drop) of the brass applicator roll and dispersing the desired volume of liquid. The pipette was then slowly raised until it disengaged from the drop and the latter came to rest on the surface of the brass applicator roll.

Because of the complexity associated with a two component starch adhesive mixture — cooked and uncooked starch — it was initially planned to use a solution of polyvinyl alcohol as the spreading fluid and spreading velocities of 150 and 450 fpm. Accordingly, a series of exploratory trials were made using an 8% PVA solution with a Stein-Hall cup viscosity of 30 seconds at 80°F

TABLE I

SUMMARY OF LIQUID DISPENSING SYSTEMS

	Method of Dispensing	Type of Dispenser	Graduations, ml	Amount Dispensed, ml	Amount Dispensed, g	Variability, %
1.	Drop 1/4 inch to surface	Hypodermic syringe	0.1	0.2	0.17	± 20
2.	Apply on surface	Hypodermic syringe	0.1	0.2	0.17	± 14
3.	Drop 1/4 inch to surface	"Manostat"	0.001	0.02	0.018	± 15
4.	Same as 3 except coat tip with silicone			0.02	0.22	± 12
5.	Drop 1/4 inch to surface	Micrometer pipette	0.002	0.06	0.068	± 14
6.	Same as 5 except coat tip with silicone			0.06	0.065	± 9
7.	Same as 5 except install teflon tip			0.06	0.61	± 3
8.	Dispense on surface with teflon tip and raise pipette up to release	Micrometer pipette	0.002	0.06	0.60	± 0.8
9.	Dispense on surface (glass tip with silicone) raise pipette to release	Micrometer pipette	0.002	0.04	0.42	± 1.0

Note: 1. For Numbers 1-8 liquid used was distilled water + dye. For Number 9 liquid used was Stayco M starch at 25% solids.
2. In 9 the teflon tip was removed when the starch solution was used as the teflon tip readily plugged and gave noticeably variable drop sizes.
3. When dispensing any liquid from the micrometer pipette, the size of the droplet varied as the barrel of the micrometer was turned. Thus, the procedure was established to always start dispensing at "0," rotate the barrel to 4 or 6 ml and form the drop. The micrometer was always reset to start.

which compares favorably with the viscosity of conventional starch adhesive. A small amount of methylene blue 2S dye was added to the solution to more clearly outline the area over which the solution was spread. Using a nip load of 14 pli, strips of calendered and uncalendered corrugating medium were tested using a 0.06 ml drop size and velocities of 150 and 450 fpm. The results obtained are tabulated in Table II.

TABLE II

EFFECT OF RATE OF SPREADING USING POLYVINYL ALCOHOL (8% PVA)

Speed, fpm	Spread Area, inch^2[a]			
	Felt Side		Wire Side	
	Uncalendered	Calendered	Uncalendered	Calendered
150	2.85	4.00	2.66	4.69 (4.72)[b]
450	2.78	4.00	2.66	4.82 (4.74)[b]

[a] Calculated from area = π L W/4.
[b] Measured by means of planimeter.

It may be seen that the speed of spreading had very little effect on the spread area. This is in direct contrast to the results obtained by Wink and Van den Akker (1) at very slow speeds and a somewhat different shaped nip — glass plate and roll, and in most cases, on oil. The spread patterns are shown in Fig. 2. It may be noted that these are elliptical in shape. Because of the rheological properties of PVA, the second trial was made using a Newtonian fluid — distilled water and a small amount of methylene blue dye. It was found that the drop size had to be reduced to 0.02 ml to keep the spread pattern within the 1.5 inches width of the paper. Typical spread patterns obtained are shown in Fig. 3. It may be noted that the spread patterns are noticeably different from the PVA and show a definite speed effect, but in the reverse order of what had been anticipated with the PVA. The addition of wetting agent to the water did not change the spread

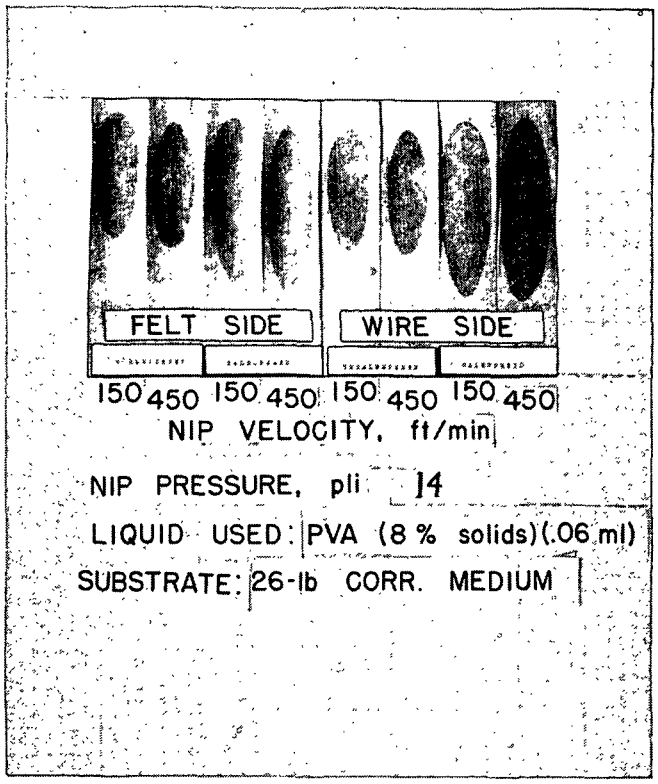


Figure 2. Appearance of Spread Patterns Using Polyvinyl Alcohol as the Test Liquid

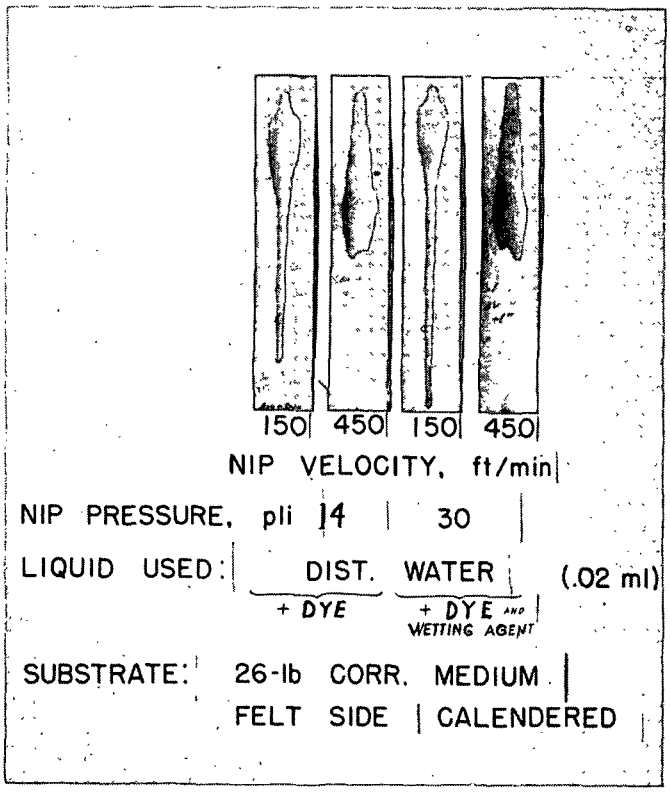


Figure 3. Appearance of Spread Patterns Using Distilled Water as the Test Liquid

pattern significantly in subsequent trials. Increasing the nip loading from 14 to 31 pli also had little effect on the spread pattern. Additional tests were made using calendered medium at a 31 pli nip loading using 4% PVA and 500 cps polyisobutene oil. Polyisobutene was used because it was felt the insensitivity of the PVA to speed might be due to its low absorption at the high speed levels used. The polyisobutene oil is not only a Newtonian material but also exhibits a good degree of absorption on a paper surface. The spread areas resulting from these tests are tabulated in Table III and are illustrated in Fig. 4.

TABLE III

COMPARISON OF RESULTS WITH VARIOUS LIQUIDS

Liquid	Nip Load, pli	Area, inch^2	
		150 fpm	450 fpm
Water + dye	14	2.52	2.46
Water, dye, and wetting agent	31	2.63	2.50
4% PVA	31	5.83	5.23
Polyisobutene oil	31	4.06	3.00

It may be noted that in all of the above cases the film density — grams of fluid per square inch of spread — was lower at the higher speed. An expanded series of trials were made to explore the effect of speed. For this purpose, four fluids — 25 and 12.5% Stayco M, 4% PVA and polyisobutene — were examined at 31 pli nip load and a speed range of 10-520 fpm. The results obtained are tabulated in Table IV and the spread patterns obtained are shown in Fig. 5. Although there was considerable variability with increase in speed, the general trend was for the spread area to be very insensitive to marked changes in speed. In most cases the spread area tended to decrease slightly with increase in speed.

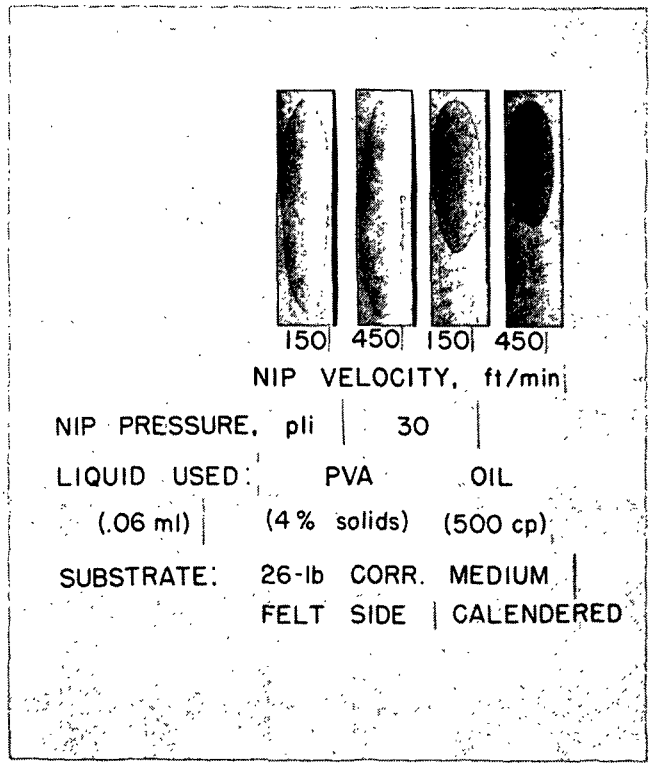


Figure 4. Appearance of Patterns Obtained with Various Liquids

As mentioned previously, the general trend was for the spread values to be essentially independent of speed, therefore, it was not possible to use this approach to evaluate roughness and permeability (surface receptivity). It may be theorized that when the selected fluid is water in contrast to oil, the measurement of permeability and roughness parameters with the aid of the two roll nip application apparatus operated at 150-450 fpm is complicated by the swelling of the fibers and the resulting changes in conditions of permeation and by the previously absent process of absorption (take-up of water by fibers themselves). The permeability factor, which otherwise was considered constant, will now depend both on the absorption into the surface and on the time. There may also be (less significant) effects on the roughness parameter. The previous assumption that the amount of fluid removed from the surface by permeation, in a given region of the sample, should be proportional to $\underline{t}^{1/2}$ (where $\underline{t}$ is the time of exposure), obviously is no longer applicable. When the apparatus is

TABLE IV

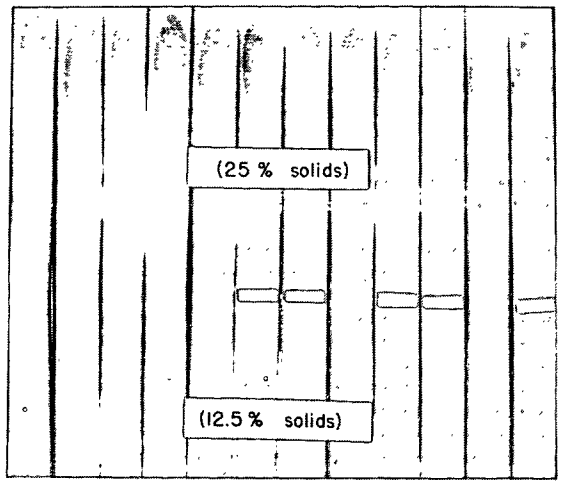
EFFECT OF SPEED ON IGT NIP FILM SPREAD AREAS

Corrugating Medium, Calendered

Spread Area, inch^2

Speed, fpm	Solids: Droplet:	Starch, Stayco M 25% 0.04 ml	Starch, Stayco M 12-1/2% 0.04 ml	PVA 4% 0.04 ml	Polyisobutene 0.06 ml
10		4.23	3.90	3.00	4.73
20		3.60	3.11	2.23	4.89
26		4.10	5.12	3.81	4.42
40		3.39	4.42	4.38	4.66
100		3.40	3.34	4.39	4.10
150		3.28	--	4.67	4.10
220		3.43	--	3.46	4.20
280		3.30	3.53	3.88	3.75
340		3.48	--	3.74	3.50
400		3.20	--	3.66	3.88
450		3.41	4.01	3.82	3.62
520		2.80	--	4.00	3.53
		Blotter Stock and Stayco M		Distilled Water (0.02 ml)	
	Droplet:	0.06 ml	0.06 ml	on 26-lb Corr. Medium Felt Side — Calendered	
10		1.93	--	1.05	
20		1.92	--	1.50	
26		1.62	1.74	1.64	
40		1.75	--	2.15	
100		1.80	1.87	2.39	
150		1.70	--	2.71	
220		1.72	--	2.50	
280		1.76	1.83	3.00	
340		1.71	--	2.00	
400		1.62	--	2.23	
450		1.55	--	2.00	
520		1.60	1.93	2.32	

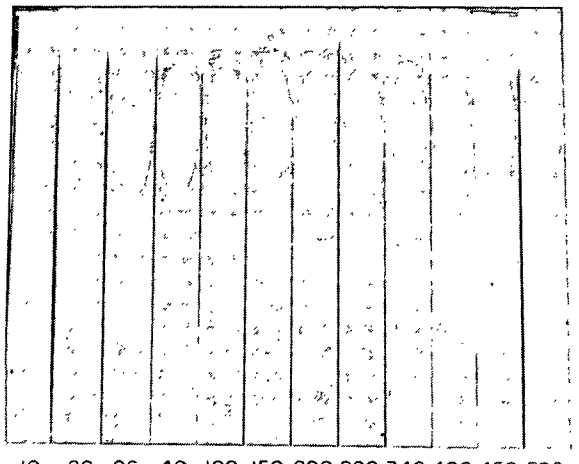
Figure 5. Effect of Speed on Spread Patterns for Various Liquids and Substrates



10 20 26 40 100 150 200 280 340 400 450 520

NIP VELOCITY, ft/min:

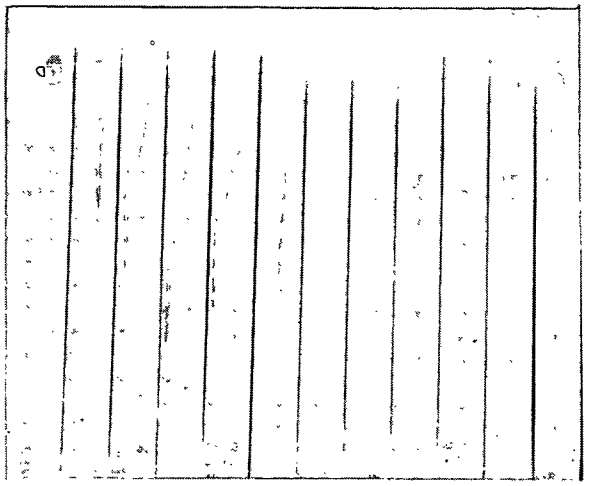
NIP PRESSURE, pli 30
LIQUID USED: STARCH (Stayco M)
SUBSTRATE: 26-lb CORR. MEDIUM FELT SIDE
CALENDERED COLD 80°F



10 20 26 40 100 150 200 280 340 400 450 520

NIP VELOCITY, ft/min:

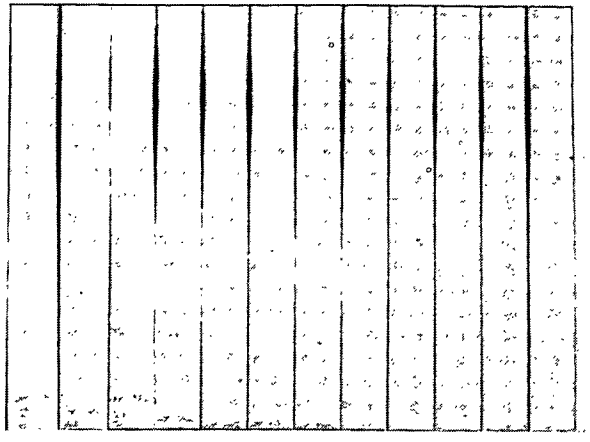
NIP PRESSURE, pli 30
LIQUID USED: OIL (500 cp) (.06 ml)
SUBSTRATE: 26-lb CORR. MEDIUM FELT SIDE
CALENDERED COLD 80°F



10 20 26 40 100 150 200 280 340 400 450 520

NIP VELOCITY, ft/min:

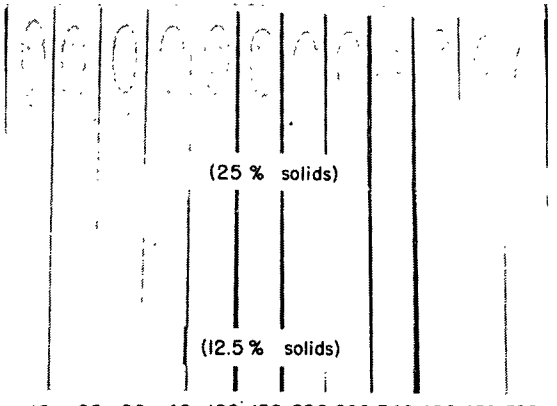
NIP PRESSURE, pli 30
LIQUID USED: DIST. WATER (.02 ml)
SUBSTRATE: 26-lb CORR. MEDIUM FELT SIDE
CALENDERED COLD 80°F



10 20 26 40 100 150 200 280 340 400 450 520

NIP VELOCITY, ft/min:

NIP PRESSURE, pli 30
LIQUID USED: PVA (4 % solids) (.04 ml)
SUBSTRATE: 26-lb CORR. MEDIUM FELT SIDE
CALENDERED COLD 80°F



10 20 26 40 100 150 200 280 340 400 450 520

NIP VELOCITY, ft/min:

NIP PRESSURE, pli 30
LIQUID USED: STARCH (Stayco M)
SUBSTRATE: BLOTTER STOCK

operated at high speed it may be argued that the shortened time of exposure will decrease the removal of fluid from the surface by permeation and absorption to the point where the fluid is removed from the "pond" largely as the consequence of surface irregularities (roughness). Under these conditions the apparatus is then primarily suited to the measurement h, the mean height of the surface irregularities, and is insensitive and unsuitable as a measurement of surface receptivity. If this simplified description is appropriate, that is, the area of spread is actually independent of speed when it is in excess of a certain minimum, the volume of fluid added, divided by the spread area, will give a measure of the roughness parameter provided the degree of wetting or film density is uniform over the spread area.

The above results may be considered in terms of hydrodynamics — the pressure built up in the nip with increasing speed. The trend of the results obtained in the preliminary phase as well as the subsequent phase of the study, agree with the findings of Arnold (3) who studied the flow properties of coating clays at high rates of shear using an inclined glass plate down which a smooth steel cylinder spread a given volume of coating. Arnold found that if a fixed volume of fluid is applied, the area of the spread pattern for most fluids decreases as the speed of the roll increases. By means of dimensional analysis, Arnold determined that the thickness of the film may be calculated from the following relationship:

$$w = k \left(\frac{N\ v}{F}\right)^a \qquad (1)$$

where: w = film thickness

N = viscosity of fluid

v = velocity of cylinder

F = weight per unit length of cylinder

k and a = constants.

In his original work, Arnold established the validity of the above relationship for Newtonian liquids such as castor oil and glycerol solutions. Hemstock and Swanson (4) have verified Arnold's findings by showing that Equation (1) is valid for Bureau of Standards oils, glycerol solutions, and for sucrose solutions when the average wet-film thickness w is greater than 6 mu. Below this value, surface irregularities of the roll and the glass plane make the errors of the method relatively great.

COMPARISON OF EXPERIMENTAL RESULTS

Using the nip film spreading technique developed in the Preliminary Trial section, nip film spreading tests were carried out using a dispersion of Stayco M in water at 25% solids. Tests were made on both felt and wire side of the calendered and uncalendered samples at two spreading rates; namely, 150 and 450 fpm. Because the results as obtained did not permit the calculation of surface receptivity and roughness, the nip film spreading results are reported in terms of (a) area of spread, and (b) estimate of surface roughness in terms of film density, the latter obtained by dividing the volume of fluid (Stayco M dispersion) applied by the area of the spread pattern.

In addition to the nip film spreading results, all the samples were evaluated for transverse bond strength (ZDT), caliper, water drop and cold water penetration. In addition, each medium was corrugated at progressively increasing speed (200-700) into A-flute single-face board on the Institute's corrugator (conventional starch adhesive) so as to be able to compare the various physical properties of the sample mediums with the pin adhesion and adhesive consumption characteristics of the combined board. As mentioned earlier, the sample mediums were corrugated in such a manner that in one case the felt side was bonded at the single-facer and in the other case the wire side was so bonded.

The physical characteristics of the mediums are tabulated in Table V and the pin adhesion and adhesive consumption results for the combined boards made with the various sample mediums are shown in Table VI. (Types of pin adhesion failure are shown in Appendix I.)

As mentioned earlier, the nip film spreading results obtained with the apparatus and conditions used in this study do not permit the calculation of the two major parameters of interest in this study; namely, surface roughness and surface receptivity. However, the results obtained on the sample mediums used in this study have been statistically analyzed with regard to the relationship between the properties of the mediums and the pin adhesion strength of the single-faced board. For the latter, the adhesion value used in the correlations for each medium is the average pin adhesion strength of the single-faced board made at 200, 300, 400, 500, and 600 fpm. The correlation coefficients based on simple linear correlations and, in two cases, logarithmic, are tabulated in Table VII, and a number of the relationships are graphically illustrated in Fig. 6 to 10, based on the calendered medium results.

When the results on the calendered samples are considered, it may be seen that there was very little difference in the level of correlation between felt and wire side, and thus the composite of felt and wire should give a more realistic assessment due to the larger number of samples. For the composite calendered results it may be observed (see Table VII) that the highest correlation coefficient was obtained for the relationship between the percent liner tear observed in the pin adhesion test and pin adhesion; the percent liner tear, of course, is not a function (at least not a direct function), of medium quality.

TABLE V

PHYSICAL CHARACTERISTICS OF CORRUGATING MEDIUMS

Sample Number	Type Surface	Caliper	Diff., %	Water Drop Number, sec		Cold Water Penetration, sec		ZDT, psi
				Felt Side	Wire Side	Felt Side	Wire Side	
5537	Uncalendered	9.2	--	66	67	1.2	1.2	84
	Calendered	6.1	-33.7	77	67	1.2	1.2	96
5540	Uncalendered	10.4	--	97	89	7.8	9.0	88
	Calendered	6.9	-33.7	61	62	4.6	4.6	96
5541	Uncalendered	9.1	--	22	21	<1	<1	96
	Calendered	6.1	-33.0	26	28	<1	<1	91
5549	Uncalendered	9.8	--	180	170	15.2	19.2	87
	Calendered	6.1	-37.8	148	156	6.0	7.0	100
5561	Uncalendered	9.2	--	42	36	2.0	2.0	82
	Calendered	5.9	-35.9	31	26	1.0	1.0	84
5576	Uncalendered	9.7	--	600+	600+	600+	600+	76
	Calendered	6.1	-37.1	600+	600+	600+	600+	95
5579	Uncalendered	10.7	--	600+	600+	600+	600+	82
	Calendered	6.9	-35.5	600+	600+	405	505	94
6348	Uncalendered	10.4	--	189	196	15.6	18.8	87
	Calendered	6.9	-33.7	118	116	10.6	10.8	97
6452	Uncalendered	10.0	--	609	547	60.0	78.4	86
	Calendered	6.3	-37.0	294	315	34.8	40.6	101

TABLE V (Continued)

PHYSICAL CHARACTERISTICS OF CORRUGATING MEDIUMS

Sample Number	Type Surface	IGT Nip Film Spread Area, inch²						Surface Density of Film, ml/in.²			
		Felt Side			Wire Side			Felt Side		Wire Side	
		150 fpm	450 fpm	Diff.	150 fpm	450 fpm	Diff.	150 fpm	450 fpm	150 fpm	450 fpm
5537	Uncalendered	1.92	2.03	0.11	1.73	2.10	0.33	0.0208	0.0197	0.0231	0.0190
	Calendered	3.45	3.89	0.44	3.46	4.07	0.61	0.0116	0.0103	0.0116	0.0100
5540	Uncalendered	1.64	2.05	0.41	2.18	2.17	-0.01	0.0244	0.0195	0.0183	0.0184
	Calendered	3.96	3.63	-0.33	3.74	4.14	0.40	0.0101	0.0110	0.0107	0.0097
5541	Uncalendered	1.94	1.97	0.03	2.17	2.20	0.03	0.0206	0.0203	0.0184	0.0182
	Calendered	3.97	4.03	0.06	4.51	4.64	0.13	0.0101	0.0100	0.0089	0.0086
5549	Uncalendered	1.60	1.48	-0.12	1.57	1.63	0.06	0.0250	0.0270	0.0255	0.0245
	Calendered	3.21	2.95	-0.26	3.51	3.37	-0.14	0.0125	0.0136	0.0114	0.0119
5561	Uncalendered	1.74	1.81	0.07	1.65	1.70	0.05	0.0230	0.0221	0.0242	0.0236
	Calendered	3.51	2.95	-0.56	3.27	3.49	0.22	0.0114	0.0136	0.0122	0.0115
5576	Uncalendered	2.42	2.56	0.14	1.96	1.90	-0.06	0.0165	0.0156	0.0204	0.0211
	Calendered	5.40	4.87	0.43	3.39	3.77	0.38	0.0074	0.0082	0.0118	0.0119
5579	Uncalendered	1.17	1.51	0.34	1.61	2.01	0.40	0.0342	0.0265	0.0248	0.0199
	Calendered	3.06	3.12	0.06	3.33	3.51	0.18	0.0131	0.0128	0.0120	0.0114
6348	Uncalendered	1.88	1.99	0.11	1.99	2.08	0.09	0.0210	0.0201	0.0201	0.0192
	Calendered	3.32	3.47	0.15	3.81	3.89	0.08	0.0105	0.0115	0.0105	0.0103
6452	Uncalendered	1.66	1.80	0.14	1.67	1.64	-0.03	0.0241	0.0222	0.0240	0.0244
	Calendered	2.65	2.85	0.20	2.69	2.70	0.01	0.0159	0.0140	0.0149	0.0148

TABLE VI

PIN ADHESION AND ADHESIVE CONSUMPTION RESULTS

Medium No.	Side Bonded	200 fpm Pin Adhesion, lb/6 in.^{2}	200 fpm Adhesive Consumpt., lb/M ft^2	300 fpm Pin Adhesion, lb/6 in.^{2}	300 fpm Adhesive Consumpt., lb/M ft^2	400 fpm Pin Adhesion, lb/6 in.^{2}	400 fpm Adhesive Consumpt., lb/M ft^2	500 fpm Pin Adhesion, lb/6 in.^{2}	500 fpm Adhesive Consumpt., lb/M ft^2
5537	Wire side	77.4	0.84	84.2	0.84	84.8	0.76	81.8	0.85
	Felt side	79.8	0.85	82.4	0.87	78.6	0.82	75.4	0.92
5540	Wire side	75.6	0.67	79.4	0.73	79.8	0.74	79.0	0.78
	Felt side	75.2	0.72	78.6	0.78	74.8	0.74	70.0	0.68
5541	Wire side	61.2	--	62.0	--	65.2	--	62.2	--
	Felt side	58.8	--	59.2	--	57.0	--	53.8	--
5549	Wire side	76.8	0.88	83.4	1.02	80.6	0.98	78.0	0.93
	Felt side	74.6	0.81	73.8	0.85	68.8	0.71	65.4	0.92
5561	Wire side	61.6	0.71	66.4	0.70	59.2	0.79	60.8	0.88
	Felt side	63.8	0.90	61.0	0.84	57.2	0.68	52.8	0.70
5576	Wire side	69.2	0.67	71.0	0.64	74.2	0.62	69.6	0.70
	Felt side	69.8	0.60	75.2	0.64	66.8	0.60	70.0	0.67
5579	Wire side	73.8	0.50	74.6	0.59	74.8	0.55	73.8	0.56
	Felt side	72.6	0.68	75.0	0.47	68.2	0.40	72.8	0.44
6348	Wire side	66.6	0.85	68.8	0.80	69.4	0.72	71.2	0.78
	Felt side	69.0	0.82	69.8	0.86	69.4	0.80	66.4	0.88
6452	Wire side	71.2	0.78	75.0	0.78	72.4	0.76	74.6	0.83
	Felt side	71.4	0.85	74.4	0.78	68.8	0.74	65.6	0.72

TABLE VI (Continued)

PIN ADHESION AND ADHESIVE CONSUMPTION RESULTS

Medium No.	Side Bonded	600 fpm		700 fpm		Average[a]		General Failure Mode[b]
		Pin Adhesion, lb/6 in.^{2}	Adhesive Consumpt., lb/M ft^2	Pin Adhesion, lb/6 in.^{2}	Adhesive Consumpt., lb/M ft^2	Pin Adhesion, lb/6 in.^{2}	Adhesive Consumpt., lb/M ft^2	
5537	Wire side	82.4	0.95	--	--	82.1	0.85	100-0
	Felt side	79.8	0.72	63.4	--	79.2	0.84	100-0
5540	Wire side	81.6	0.80	--	--	79.1	0.74	76-24
	Felt side	68.2	0.72	64.4	--	73.4	0.73	58-42
5541	Wire side	61.4	--	--	--	62.4	--	0-100
	Felt side	54.4	--	48.8	--	56.6	--	0-100
5549	Wire side	81.6	0.93	--	--	80.1	0.97	40-60
	Felt side	67.4	0.88	59.0	--	70.0	0.83	10-90
5561	Wire side	55.0	0.84	--	--	60.6	0.78	6-94
	Felt side	51.2	0.99	47.2	--	57.2	0.82	0-100
5576	Wire side	72.6	0.68	--	--	71.3	0.66	14-86
	Felt side	66.2	0.62	65.2	--	69.6	0.63	26-74
5579	Wire side	75.8	0.68	--	--	74.6	0.58	38-62
	Felt side	71.2	0.48	65.4	--	72.0	0.49	58-42
6348	Wire side	66.2	0.86	--	--	68.4	0.82	24-76
	Felt side	62.6	0.87	51.2	--	67.4	0.85	24-76
6452	Wire side	71.4	0.92	--	--	72.9	0.81	28-72
	Felt side	65.0	0.74	60.4	--	69.0	0.77	38-62

[a] Average of results at 200, 300, 400, 500, and 600 fpm.

[b] First value is the percentage of failure involving liner fiber bond and/or liner adhesive interface averaged over the speed range of 200-600 fpm. The second value is the corresponding percentage failure involving the medium fiber bond and/or medium adhesive interface.

TABLE VII

CORRELATION BETWEEN PIN ADHESION AND MEDIUM PROPERTIES

Property	Correlation Coefficient					
	Felt Side Adhesion		Wire Side Adhesion		Composite Felt & Wire Adhesion	
	Cal. N = 9	Uncal. N = 9	Cal. N = 9	Uncal. N = 9	Cal. N = 18	Uncal. N = 18
Caliper	0.36	0.41	0.26	0.34	0.30	0.36
Water drop, log	0.50	0.47	0.37	0.36	0.41	0.39
linear	0.29	0.27	0.15	0.14	0.21	0.19
Cold water penetration, log	0.31	0.30	0.17	0.19	0.23	0.24
linear	0.18	0.21	0.04	0.05	0.11	0.12
IGT area, 150 fpm	-0.08	-0.13	-0.25	-0.22	-0.16	-0.13
450 fpm	0.10	0.05	-0.14	0.03	0.04	0.05
Liner tear, %	0.87	0.87	0.86	0.86	0.83	0.83
ZDT bonding strength	0.65	-0.35	0.71	-0.16	0.65	-0.24
0.05 Level of significance	0.67	0.67	0.67	0.67	0.47	0.47
0.01 Level of significance	0.80	0.80	0.80	0.80	0.59	0.59

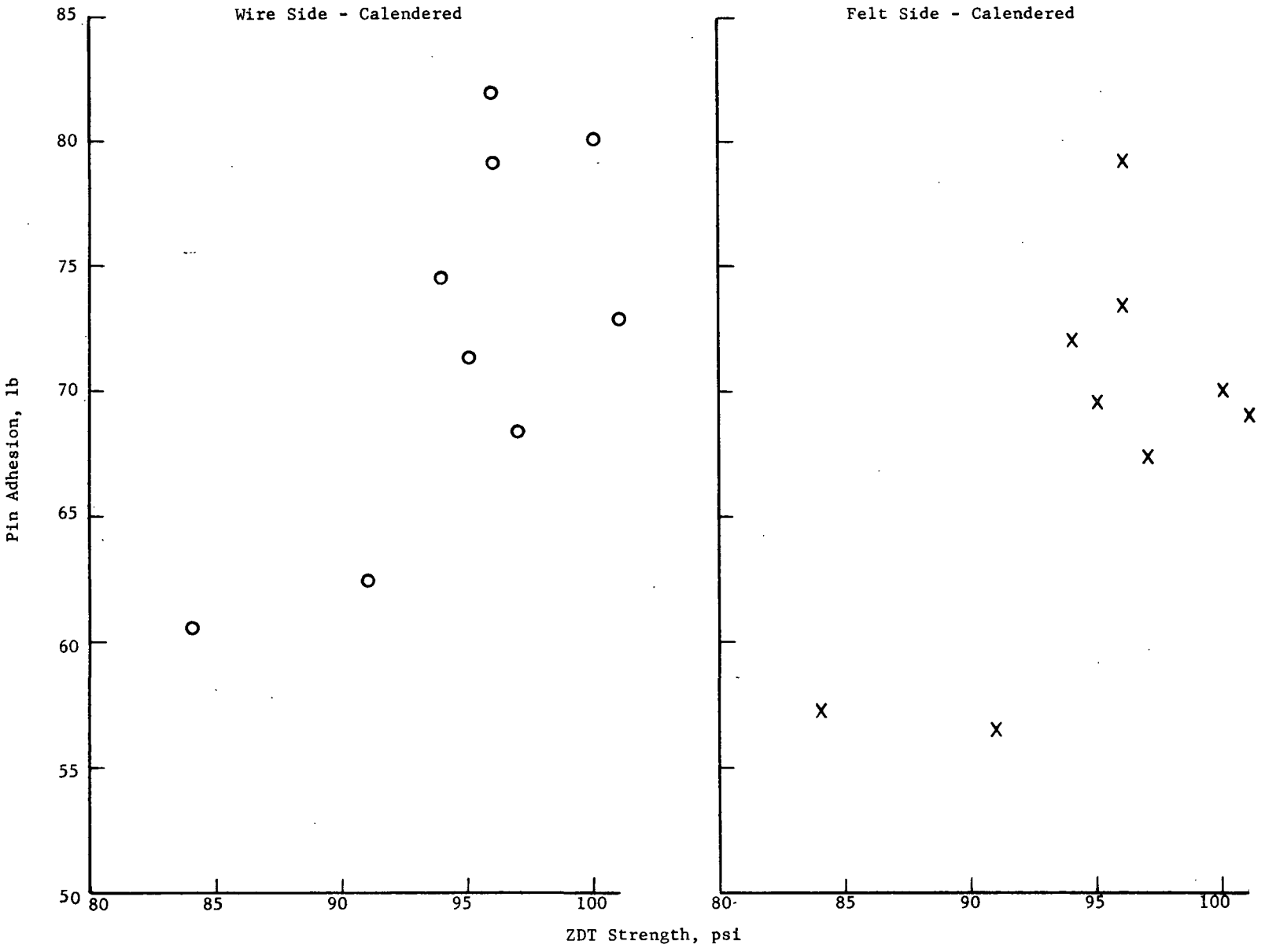


Figure 6. Relationship Between Pin Adhesion Strength and the ZDT Strength for Calendered Medium Samples

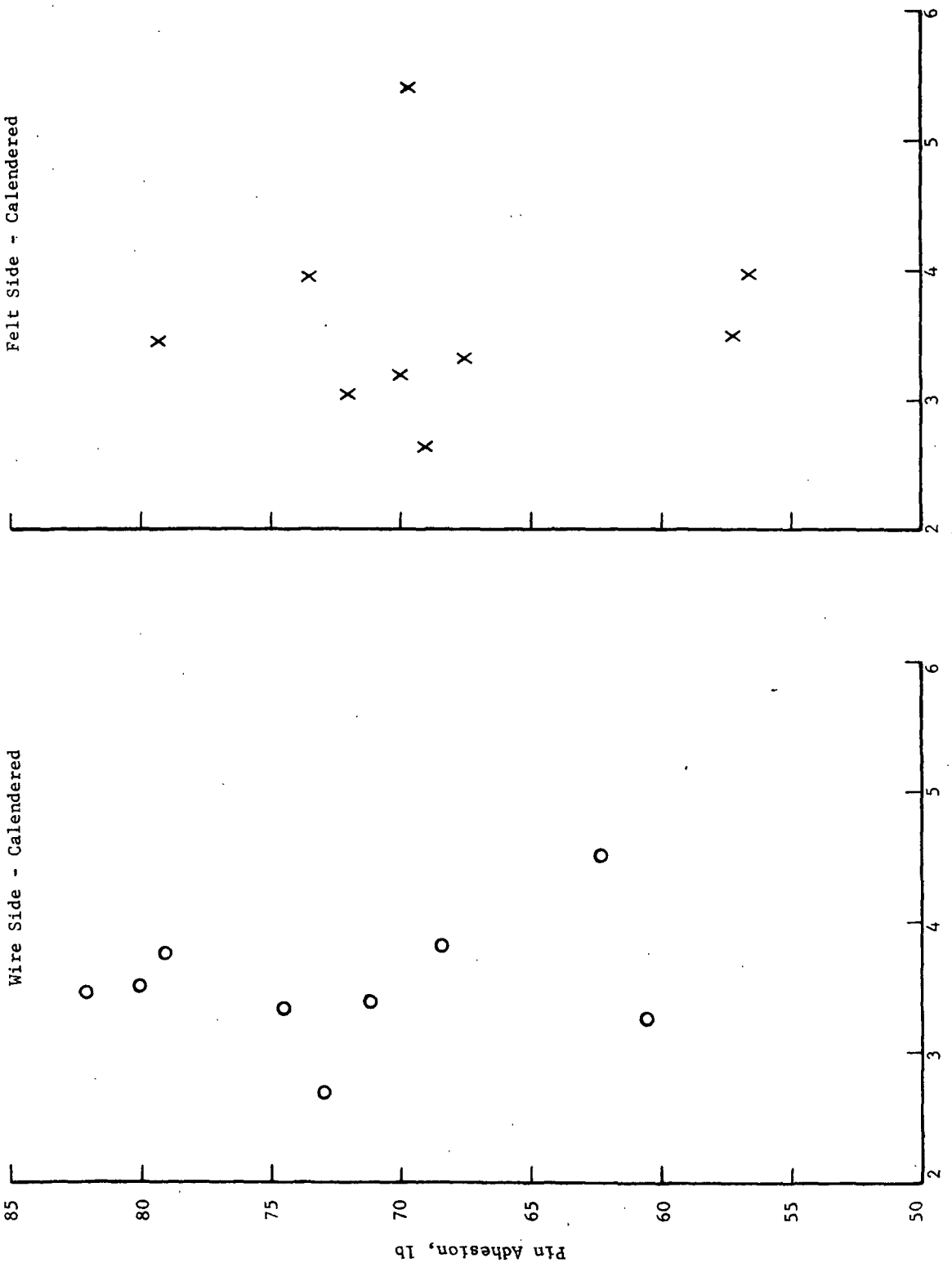


Figure 7. Relationship Between Pin Adhesion Strength and the IGT Nip Film Spread Area Determined at a Spreading Rate of 150 fpm for Calendered Medium Samples

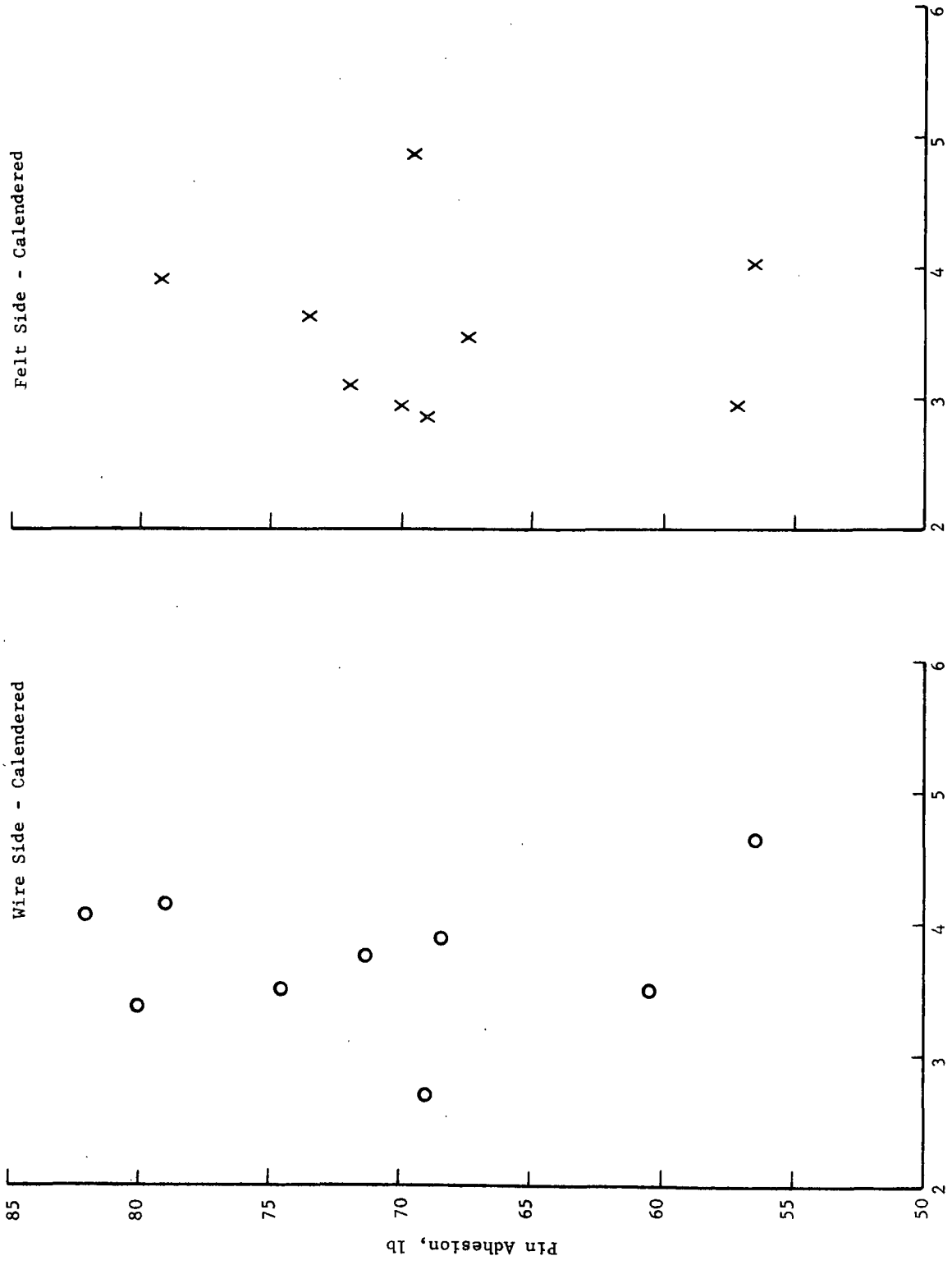


Figure 8. Relationship Between Pin Adhesion Strength and the IGT Nip Film Spread Area Determined at a Spreading Rate of 450 fpm for Calendered Medium Samples

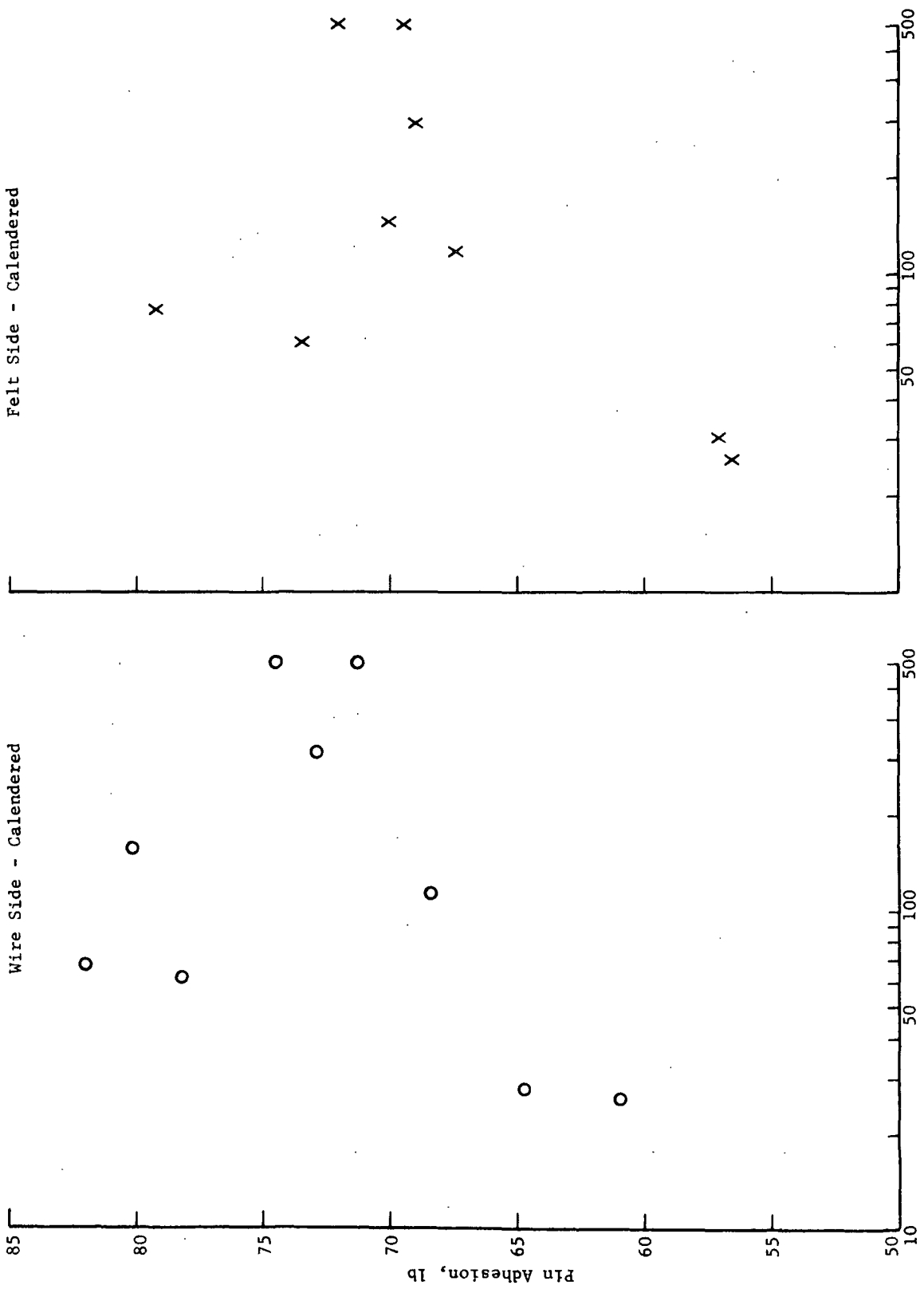


Figure 9. Relationship Between Pin Adhesion Strength and the Water Drop Number for Calendered Medium Samples

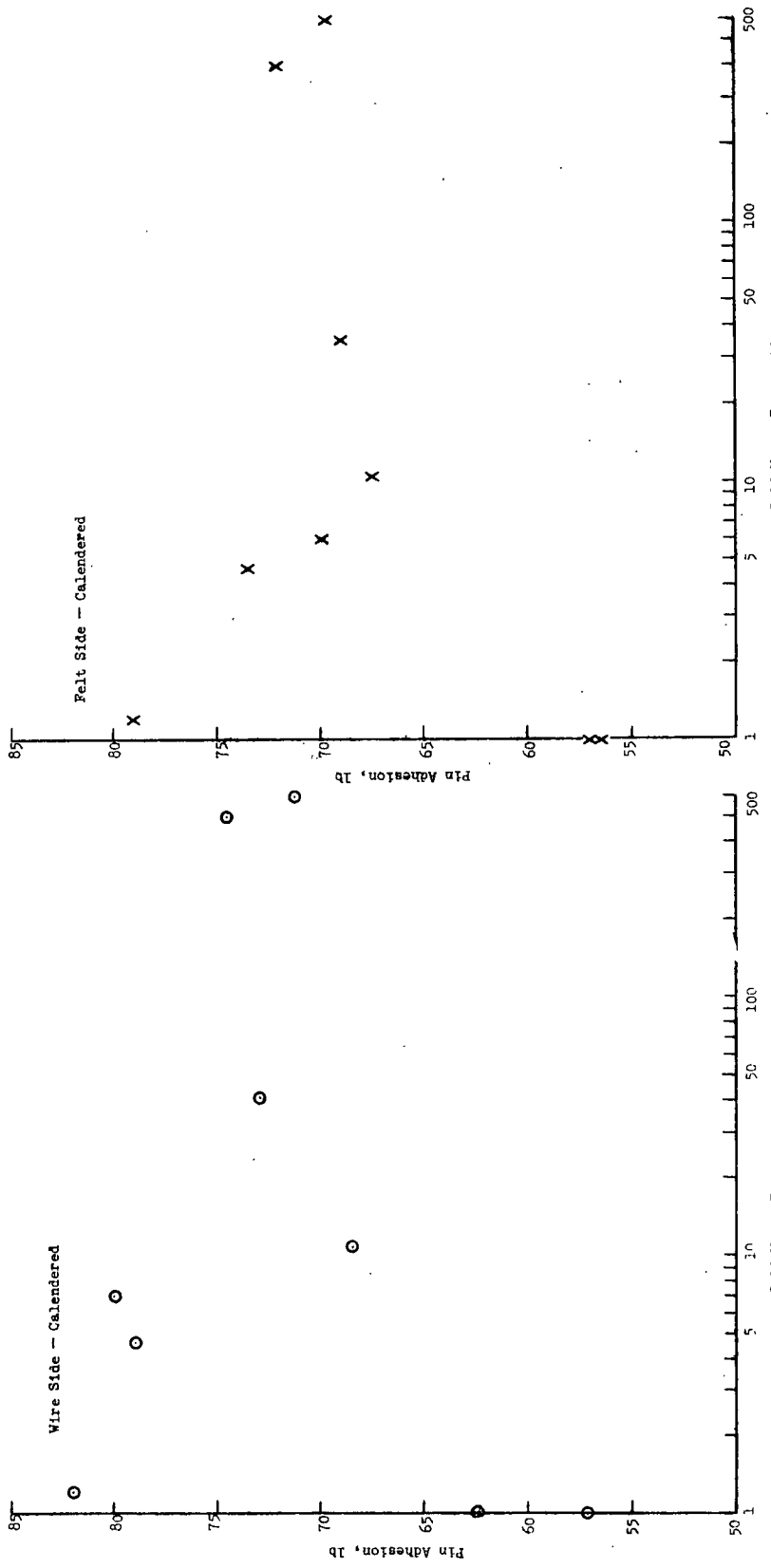


Figure 10. Relationship Between Pin Adhesion Strength and the Cold Water Penetration Number for Calendered Medium Samples

The transverse bond strength, measured by means of the ZDT tester, exhibited the next highest correlation. Both the percent liner tear and the ZDT bond strength were significant at the 0.01 level. Because of the limited number of sample lots evaluated, the correlations should be viewed with caution because the coefficients can be greatly influenced by a few data points.

In general, it may be expected that the adhesion strength should depend in part on the transverse bond strength of the medium, and this probably explains the significant correlation between pin adhesion and ZDT strength although the correlations were greatly influenced by the results for Samples 5561 and 5541 which exhibited somewhat lower ZDT strengths after calendering and pin adhesion strengths than the other samples. The positive sign for this coefficient is also in the expected direction — i.e., the higher the ZDT strength, the higher the pin adhesion.

Neither water drop nor cold water penetration were significantly related to pin adhesion strength for either the felt, wire or composite calendered results although water drop exhibited somewhat higher coefficients than cold water penetration. The correlations for water drop were influenced to a considerable extent by the results for Samples 5541 and 5561 which also exhibited somewhat lower ZDT strength after calendering as mentioned above. Both samples exhibited quite low water drop values (less than about 30 in the calendered state) and low pin adhesion strengths. If these samples were omitted, the water drop values would probably be negatively correlated with pin adhesion strength which would be more in accord with the usual experience that adhesion strength tends to decrease for mediums with very high water drop numbers. Much the same comments might be made for the cold water penetration correlations as the cold water penetration and water drop tests were quite highly correlated.

When the results on the uncalendered mediums are considered, it may be seen that the correlations generally show the same trends as were observed above for the calendered samples except that ZDT strength was not significantly related to pin adhesion strength in this case.

The intercorrelations of the various physical properties of the corrugating medium and pin adhesion in terms of correlation coefficients are tabulated in Tables VIII and IX. When the results for the calendered samples are considered, it may be seen that there was no essential difference due to felt and wire side. The same trend may be observed for the uncalendered samples. Based on the composite (felt and wire side) correlations tabulated in Table IX, it may be seen that the following were significantly related at the 0.05 level:

1. Calendered samples
   a. Pin adhesion and ZDT ($\underline{r} = 0.65$)
   b. Log cold water penetration and log of water drop number ($\underline{r} = 0.95$)
   c. IGT nip film spread area at 150 and corresponding area at 450 fpm ($\underline{r} = 0.87$)
   d. ZDT and log of water drop ($\underline{r} = 0.54$)
2. Uncalendered samples
   a. Log of water drop and caliper ($\underline{r} = 0.67$)
   b. Log cold water penetration and caliper ($\underline{r} = 0.66$)
   c. Log cold water penetration and log of water drop ($\underline{r} = 0.94$)
   d. IGT nip film spread area at 150 fpm and corresponding area at 450 fpm ($\underline{r} = 0.84$)
   e. ZDT and log water drop number ($\underline{r} = -0.60$)
   f. ZDT and log cold water penetration ($\underline{r} = -0.62$)

TABLE VIII

INTERCORRELATIONS

(Each side separately)

Property	Caliper	Water Drop, log	Cold Water Penetration, log	IGT Area 150 fpm	IGT Area 450 fpm	ZDT
			Felt Side — Cal. (N = 9)			
Pin adhesion	0.36	0.50	0.31	-0.08	0.10	0.65
Caliper	1.00	0.29	0.35	-0.22	-0.14	0.32
Water drop, log		1.00	0.95	0.06	0.09	0.52
Cold water penetration, log			1.00	0.24	0.21	0.33
IGT area, 150 fpm				1.00	0.90	-0.25
450 fpm					1.00	0.12
			Wire Side — Cal. (N = 9)			
Pin adhesion	0.26	0.37	0.17	-0.26	-0.14	0.71
Caliper	1.00	0.30	0.35	0.10	0.07	0.32
Water drop, log		1.00	0.96	-0.54	-0.53	0.56
Cold water penetration, log			1.00	-0.43	-0.42	0.34
IGT area, 150 fpm				1.00	0.92	-0.26
450 fpm					1.00	-0.34
			Felt Side — Uncal. (N = 9)			
Pin adhesion	0.41	0.47	0.30	-0.13	0.05	-0.35
Caliper	1.00	0.67	0.65	-0.52	-0.24	-0.16
Water drop, log		1.00	0.93	-0.13	-0.01	-0.60
Cold water penetration, log			1.00	-0.10	0.07	-0.62
IGT area, 150 fpm				1.00	0.89	-0.20
450 fpm					1.00	-0.30
			Wire Side — Uncal. (N = 9)			
Pin adhesion	0.34	0.36	0.19	-0.22	0.03	-0.16
Caliper	1.00	0.67	0.67	-0.01	0.09	-0.16
Water drop, log		1.00	0.94	-0.35	-0.34	-0.60
Cold water penetration, log			1.00	-0.24	-0.26	-0.61
IGT area, 150 fpm				1.00	0.74	0.43
450 fpm					1.00	0.36

Note: Significance levels are as follows: 0.05 level, $r = 0.666$; 0.01 level, $r = 0.798$.

TABLE IX

INTERCORRELATIONS

(Composite of felt and wire side results)

Property	Caliper	Water Drop, log	Cold Water Penetration, log	IGT Area 150 fpm	IGT Area 450 fpm	ZDT
			Calendered — Felt-Wire (N = 18)			
Pin adhesion	0.30	0.41	0.23	-0.16	0.04	0.65
Caliper		0.29	0.35	-0.10	-0.05	0.32
Water drop, log			0.95	-0.17	-0.19	0.54
Cold water penetration, log				-0.02	-0.07	0.34
IGT area, 150 fpm					0.87	-0.25
450 fpm						-0.19
			Uncalendered — Felt-Wire (N = 18)			
Pin adhesion	0.36	0.39	0.24	-0.13	0.05	-0.24
Caliper		0.67	0.66	-0.30	-0.10	-0.16
Water drop, log			0.94	-0.22	-0.14	-0.60
Cold water penetration, log				-0.15	-0.07	-0.62
IGT area, 150 fpm					0.84	0.06
450 fpm						-0.02

Note: Significance levels are as follows: 0.05 level, $r = 0.468$; 0.01 level, $r = 0.590$.

As noted above, the water drop and cold water penetration tests were highly correlated for both the uncalendered and calendered mediums. This indicates that both tests measure essentially the same property of the medium. Also, neither water penetration test was significantly related to the IGT nip film spread areas. This lack of correlation seems to be in accord with expectations since the IGT areas may be primarily dependent on surface irregularities rather than liquid receptivity as discussed previously.

The data do not appear to warrant a comprehensive treatment in terms of analysis because it was not possible to achieve the primary objective; namely, to calculate surface roughness and surface receptivity. Nevertheless, a few miscellaneous comparisons involving such things as pin adhesion, adhesive consumption, water drop number, etc., may be made since the data are available. When the adhesive consumption is averaged over the 200-600 fpm range, it may be seen that the trend is for the wire side to pick up slightly more adhesive than the felt side presumably due to being more open and hence, porous. The relationship between pin adhesion and the average adhesive consumption may be seen in Fig. 11. It may be noted that there appears to be very poor relationship between these two quantities for the very limited range of adhesive pick-ups which were obtained. These results imply that more is involved in pin adhesion than the amount of pick-up where only small variations in pick-up are involved. Usually when the pick-up is varied over a greater range, pin adhesion strength increases as pick-up is increased.

Two other comparisons have also been made; namely, the relationship between water drop, nip film spread areas and adhesive consumption. These are shown graphically in Fig. 12 and 13, respectively. When the water drop versus adhesive consumption data are considered, it may be seen that there might be a

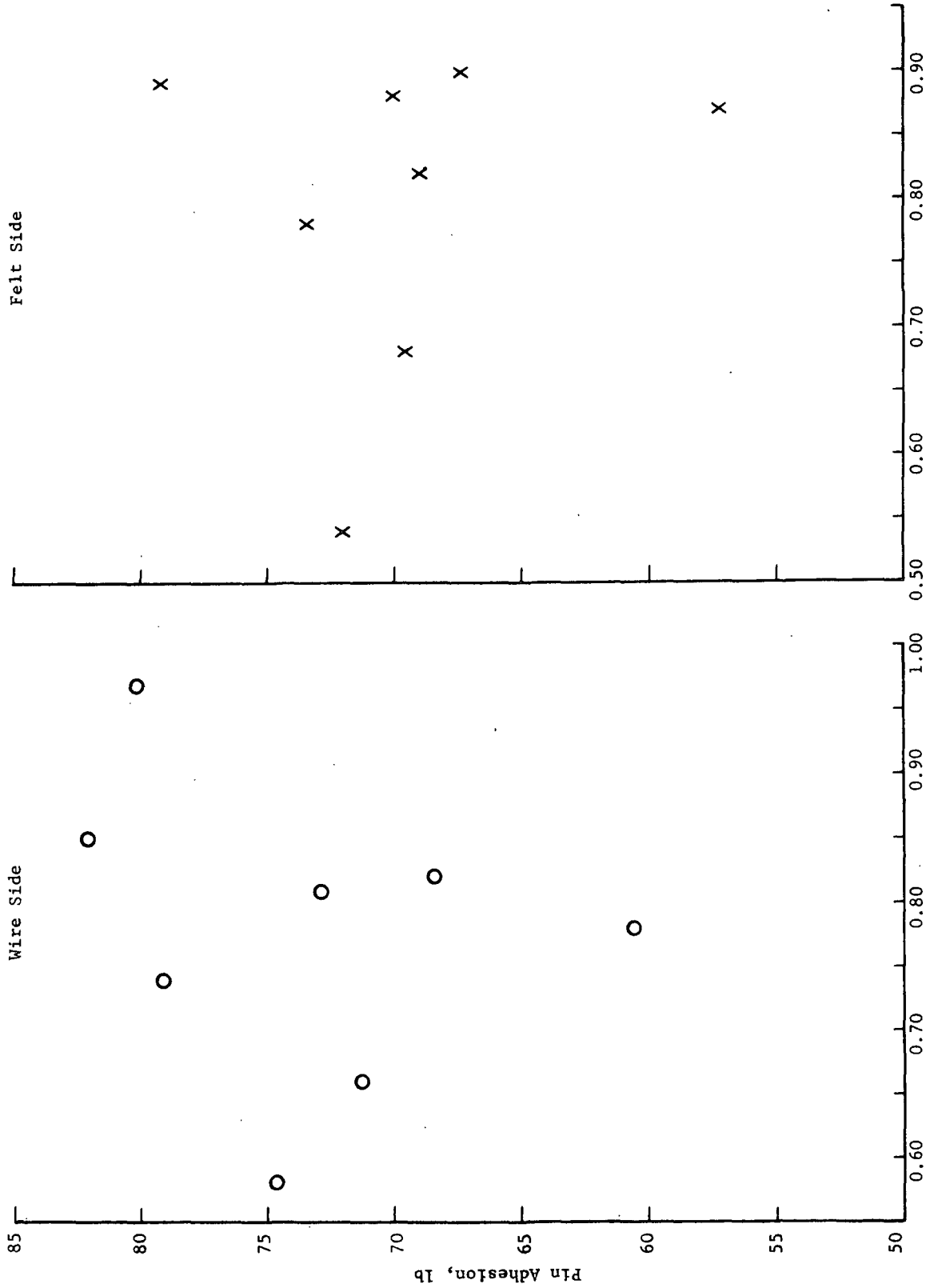


Figure 11. Relationship Between Pin Adhesion Strength and Average Adhesive Consumption

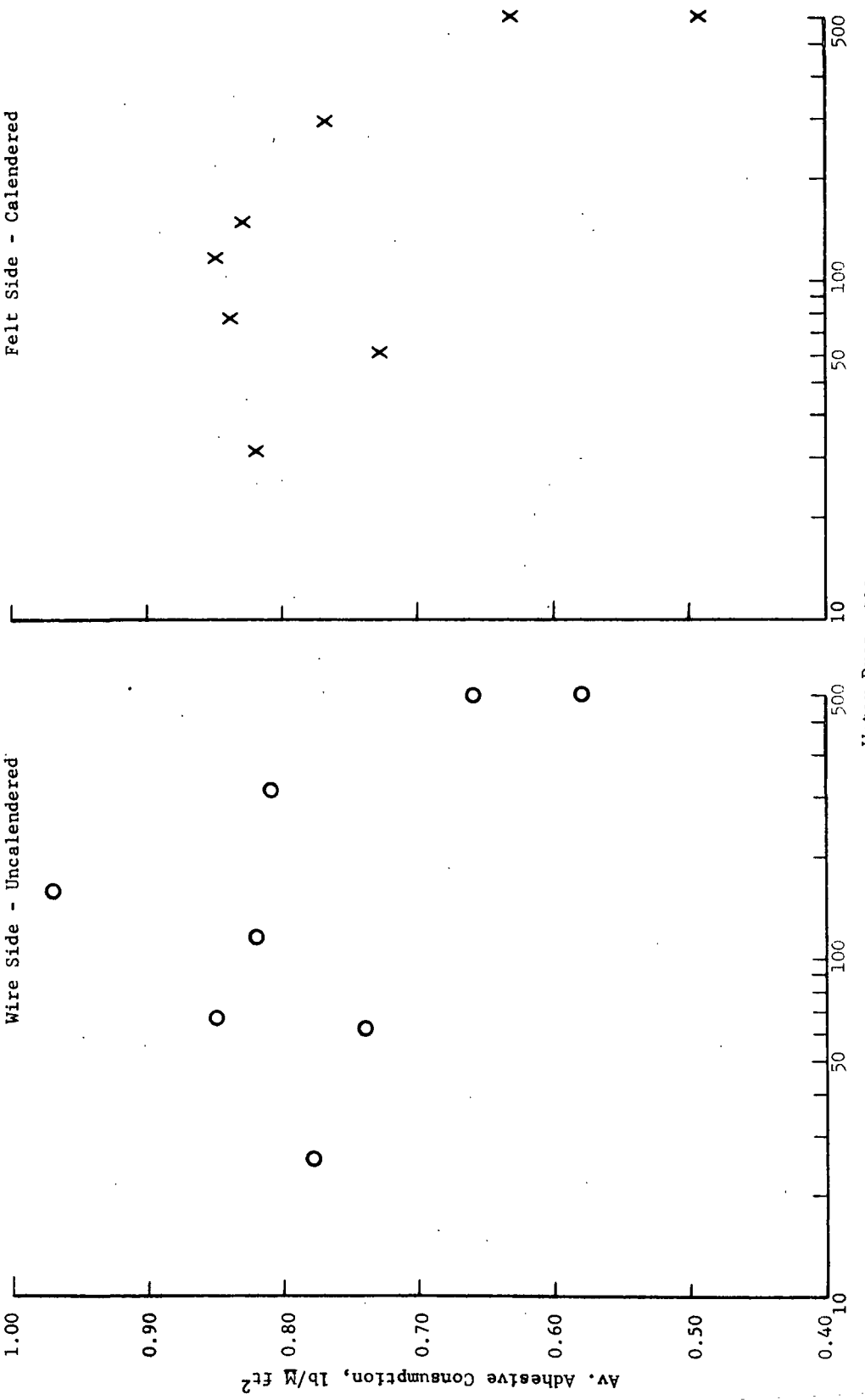


Figure 12. Relationship Between Average Adhesive Consumption and Water Drop

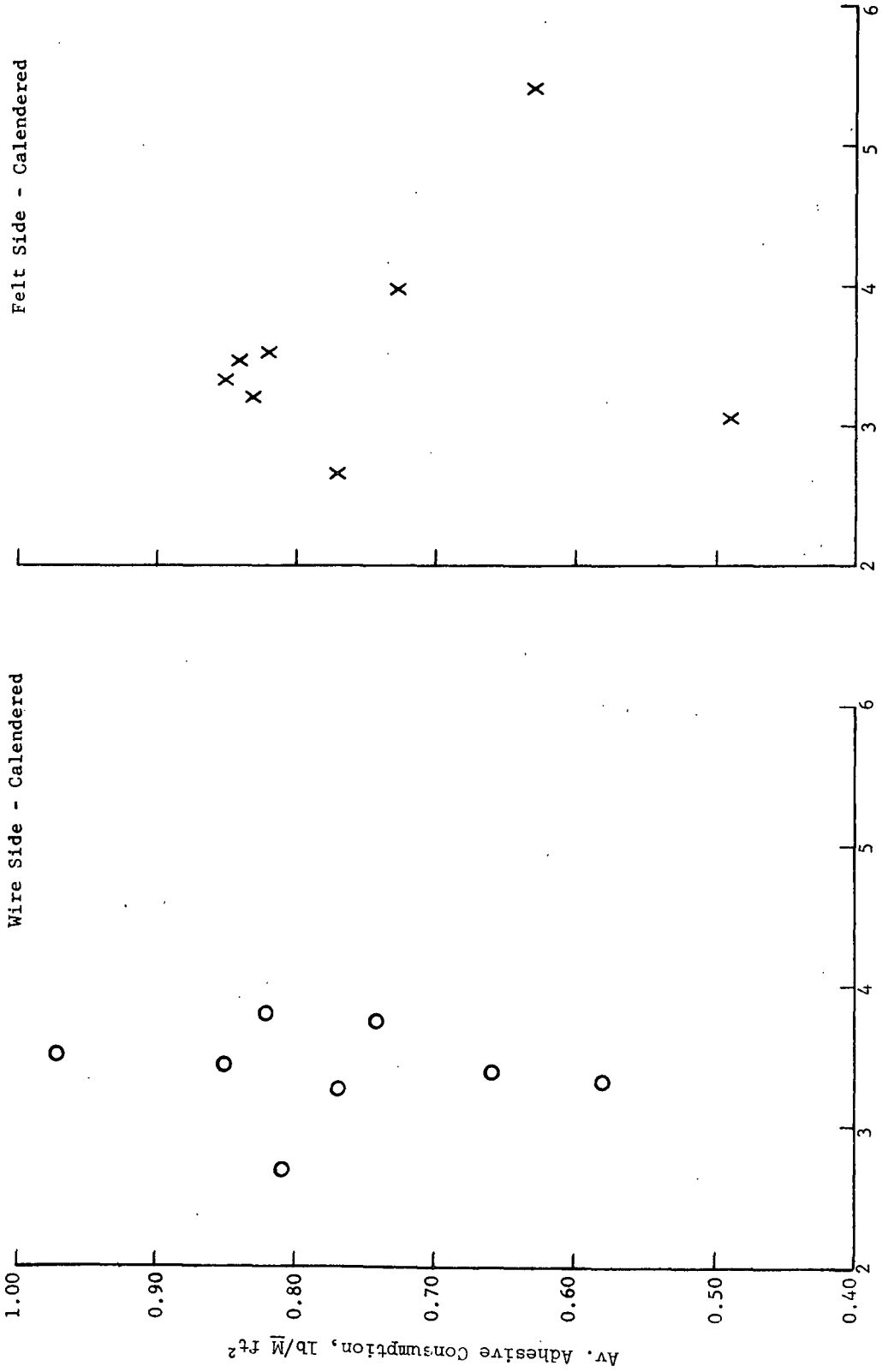


Figure 13. Relationship Between Average Adhesive Consumption and IGT Nip Film Spread Area Obtained at a Spreading Rate of 150 fpm

trend for the adhesive consumption to decrease with increase in the log of the drop test number although the data are quite variant. In contrast, when the IGT nip film spread area at 150 fpm is plotted against adhesive pick-up, the results indicate that the IGT areas are, at best, very poorly related to adhesive consumption. It should be borne in mind in interpreting these results that this study embraces a very limited number of samples.

In general, the properties of the corrugating medium which may be expected to influence the pin adhesion strength of corrugated board are those which (1) affect the nature of the contact developed between the adhesive and the components, and (2) the fiber-to-fiber bonding strength of the components. Thus, it is believed that corrugating medium should have the following characteristics to obtain satisfactory adhesion to the linerboard: (1) a relatively open porous structure, (2) a somewhat rough surface (provided the surface can be wetted) so that the total area available for bonding is greater than would be obtained if the surface were smooth, (3) a hydrophilic surface easily wet by the aqueous adhesive, and (4) high fiber-to-fiber bonding strength compatible with attainment of other properties.

The above should be considered in terms of the calendered state of the medium tips at the time of adhesive application. Past studies have shown that the calendering action tends to (1) close up the larger pores and hence reduce the "average" pore size, (2) increase smoothness, (3) decrease porosity, and (4) usually increase the receptivity somewhat. The effect of calendering on transverse bonding strength is somewhat uncertain since opposite results are obtained depending on the method of measurement. For example, in past work the bonding strength generally decreased after calendering when measured in terms of (a) IGT bonding strength, and (b) Z-direction tensile strength wherein the sheet was bonded

to steel cylinders with epoxy adhesive before being pulled apart. On the other hand, the ZDT tests employed herein indicated that the transverse bonding strength increased after calendering. In the ZDT tests, a two-side tape is used to adhere the specimen to the steel pulling blocks and the contact between tape and specimen may not be entirely "ideal" for the "rough" uncalendered medium surfaces, thus, giving rise to the lower rupture loads for the uncalendered specimens.

From the above it appears that the actual pin adhesion strength achieved after the single-facing operation can be expected to be a function of such properties as the surface receptivity, roughness or smoothness, porosity, contact angle and fiber-to-fiber bond strength of the sheet. Past results indicate that such properties may be related to pin adhesion but that no one property is very dominant.

LITERATURE CITED

1. Wink, W. A. and Van den Akker, J. A. A new apparatus and procedure for determining the surface recptivity and roughness of paper as these relate to liquid film application. Tappi 40(7):528-36(July, 1957).

2. Hung, J. Y., Nelson, R. W., and Van Eperen, R. H. Remarks on the surface receptivity and roughness of paper as these relate to liquid film application. Tappi 52(9):1732-4(Sept., 1969).

3. Arnold, K. A. Flow properties of coating clays at high rates of shear. Paper Trade J. 117(9):28-34(Aug. 26, 1943).

4. Hemstock, G. A. and Swanson, J. W. A study of the penetration of coating color components by means of the roll-inclined plane technique. Tappi 40 (10):833-8(Oct., 1957).

THE INSTITUTE OF PAPER CHEMISTRY

Carl N. Smith
Research Assistant

William J. Whitsitt
Research Associate

R. C. McKee
Director
Container Section